Brachial Plexus

Patients are usually referred to MR because of typical brachial plexus symptoms, which include pain, numbness or weakness of the shoulder or arm. MR is the primary imaging modality used to diagnose the cause of brachial plexopathy.

The Basic Protocol is the core component of this procedure. When a specific cause of brachial plexopathy is suspected, modification of the Basic Protocol may be necessary. For example, if the patient is suspected of having avulsion injury from trauma, use Alternate Protocol 1. If neoplastic involvement of the brachial plexus is suspected or any abnormalities are seen, use of intravenous contrast material is helpful (Alternate Protocol 2). When the patient has symptoms of thoracic outlet syndrome and vascular compression is suspected, contrast enhanced MRA (magnetic resonance angiography) can be added (Alternate Protocol 3).

The Basic Protocol takes ~30 min, and Alternate Protocols take ~45 min.

The parameters suggested here are based on experience with the Siemens 1.5 T Vision or Symphony and 1.0 T Impact scanner and should be altered accordingly for different field strengths and manufacturers. The flip angle of all turbo spin echo (fast spin echo) sequences in the tables represents the refocusing pulse. The first pulse of turbo spin echo sequences is 90°.

IMAGING OF BRACHIAL PLEXUS

BASIC PROTOCOL

The brachial plexus has a relatively long and oblique course. The brachial plexus is formed by C5 to T1 nerve roots, and runs along the subclavian and axillary arteries. Images are obtained in transverse, coronal, and sagittal planes. A T_1-weighted sequence is best for delineating the anatomy with little motion artifact, and T_2-weighted images with fat suppression are helpful in characterizing the lesion. Flow-sensitive gradient echo sequences may be used when it is difficult to differentiate vascular structures from the lesion.

Table A14.1.1 lists the hardware necessary to perform the procedure, along with appropriate parameters. The available gradient strength will depend on the scanner, and the echo times given in other tables may need to be varied accordingly (the smaller the gradient strength, the longer the echo time for a particular scan).

NOTE: Be sure that technologists and nurses have immediate access to any emergency equipment that may be relevant to a given study, or that may be needed for a particular patient, such as crash carts or oxygen.

Set up patient and equipment

1. Interview (screen) the patient to ensure that he or she has no contraindications such as cardiac pacemakers or defibrillator or other implants containing ferromagnetic materials. Also be sure to find out if the patient has any health conditions that may

Table A14.1.1 Equipment Parameters for Brachial Plexus

Coil type	Torso phased-array coil or large flex coil
Gradient coil strength	25 mT/m (or whatever the system permits)
Cardiac gating	No
Peripheral gating	No
Use of contrast agent	Yes, only used in Alternate Protocols 2 and 3

Contributed by Naoki Takahashi and Vamsidhar Narra
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require the presence of special emergency equipment during the scanning procedure, or necessitate any other precautions.

Generally standard screening forms are used for all patients scanned in a magnetic resonance system.

The presence of any ferromagnetic metals may be a health hazard to the patient when he or she is inside the magnet, and will also affect the imaging. If in doubt as to the exact composition of the items, it is best to exclude patients with any metal implants; see Shellock (1996) for discussion of what implants may be safely scanned using magnetic resonance.

Patients may be accompanied into the magnet room by a friend or family member, who can sit in the room during the scan and comfort the patient as needed. This companion must be screened as well to ensure the absence of loose metal objects on the body or clothing.

2. If the procedure is a research protocol, have the patient sign any necessary consent form.
3. Have the patient remove all jewelry and change into a gown to eliminate any metal that might be found in clothing.
4. Have the patient wash off any mascara and other makeup to avoid local tissue heating and image artifacts.
5. Inform the patient about what will occur during the procedure, what he or she will experience while in the magnet, and how to behave, including the following:
   a. If earphones or headphones are used to protect the ears from the loud sounds produced by the gradients, the patient will be asked to wear these, but will be able to communicate with you at any time during the imaging.
   b. The patient will be given a safety squeeze-bulb or similar equipment to request assistance at any time (demonstrate how this works).
   c. For good results the patient should not talk, and should avoid or minimize swallowing or other movement, during each scan—i.e., as long as the banging sounds continue. Between scans, talking and swallowing are allowed in most cases, but should be avoided when comparative positional studies are being performed; the patient will be informed when this is the case.
   d. Nevertheless, the patient may call out at any time if he or she feels it necessary.

   All the sequences are nonbreath-hold except for MRA sequence in Alternate Protocol 3 for suspected thoracic outlet syndrome.
6. Help the patient mount onto the table. Either before or right after the patient lies down, set up other monitoring equipment that is to be used.
7. Place the phased array coil high on the chest and neck. Place a towel as a block around the neck to support the coil.

   A large flex coil can also be used, but it is more difficult to position properly and has a smaller FOV (field of view).
8. If needed, place a pillow or other support under the knees to make the patient more comfortable.
9. Use the centering light to position the patient with the center at the patient's sternum and put him or her into the center of the magnet.

Sequence 1: Rapid three-plane positioning scout

10. For localization of subsequent acquisitions, run the system's three-plane scout scan according to Table A14.1.2.

Table A14.1.2 Primary Clinical Imaging Parameters for Pilot Scan (Sequence 1)

Patient position	Supine
Scan type	Gradient echo
Imaging plane (orientation)	Three-plane: transverse, coronal, and sagittal
Central slice or volume center	Upper chest
Echo time (T_E)	3.1 msec
Repeat time (T_R)	6.5 msec
Flip angle (FA)	80°
Fields of view (FOV_x, FOV_y)	450 mm, 450 mm
Resolution (Δx, Δy)	1.76 mm, 2.34 mm
Number of data points collected (N_x, N_y)	256, 192
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	5 mm
Number of slices	7
Slice gap	Variable
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
Slice locations	Variable
Saturation pulses	No
Scan time	8 sec

Sequence 2: 2-D Coronal T_1-weighted turbo spin echo scan of bilateral brachial plexus

Use the images from this coronal T_1-weighted turbo spin echo sequence for an overview of the bilateral brachial plexus. This is the only sequence obtained for the contralateral side. The image of the contralateral brachial plexus would serve as a normal control to check for symmetry.

11. Position a series of coronal slices off the scout images to ensure coverage of the bilateral brachial plexus by including both acromioclavicular joints from side to side, and mid C4 to below axilla from top to bottom. From anterior to posterior, start from slightly anterior to the subclavian and axillary artery to slightly posterior to the neural foramina of C4 to T1.
12. Run sequence 2 according to Table A14.1.3.

Sequence 3: 2-D Transverse T_1-weighted spin echo sequence of symptomatic brachial plexus

13. Position a series of transverse slices off the coronal T_1-weighted images to ensure coverage of the symptomatic brachial plexus by including mid vertebral body to the acromioclavicular joint from side to side, and mid C4 to axilla from top to bottom.
14. Run sequence 3 according to Table A14.1.4.

Sequence 4: 2-D Sagittal T_1-weighted spin echo sequence of symptomatic brachial plexus

15. Position a series of sagittal slices off the coronal T_1-weighted images from the anterior scalene muscle to slightly lateral to the acromioclavicular joint.
16. Run sequence 4 according to Table A14.1.5.

Table A14.1.3 Primary Clinical Imaging Parameters for 2-D Coronal T_1-Weighted Turbo Spin Echo (Sequence 2)

Patient position	Supine
Scan type	Fast spin echo
Imaging plane (orientation)	Coronal
Central slice or volume center	Midline
Echo time (T_E)	12 msec
Echo train length (ETL)	3
Repeat time (T_R)	875 msec
Flip angle (FA)	160°[a]
Fields of view (FOV_x, FOV_y)	375 mm, 375 mm
Resolution (Δx, Δy)	0.73 mm, 1.46 mm
Number of data points collected (N_x, N_y)	512, 256[b]
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	5 mm
Number of slices	15
Slice gap	1 mm
Number of acquisitions (N_{acq})	3
Swap read and phase encoding	No
Saturation pulses	Inferior and superior
Scan time	4 min, 54 sec

[a]The system displays the flip angle of the refocusing pulse. The flip angle of the first pulse of this sequence is 90°.
[b]30% phase oversampling.

Table A14.1.4 Primary Clinical Imaging Parameters for 2-D Transverse T_1-Weighted Spin Echo (Sequence 3)

Patient position	Supine
Scan type	Spin echo
Imaging plane (orientation)	Transverse
Central slice or volume center	Symptomatic brachial plexus
Echo time (T_E)	14 msec
Repeat time (T_R)	500 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	200 mm, 200 mm
Resolution (Δx, Δy)	0.78 mm, 1.04 mm
Number of data points collected (N_x, N_y)	256, 192[a]
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	5 mm
Number of slices	20
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Swap read and phase encoding	No
Saturation pulses	No
Scan time	3 min, 53 sec

[a]20% phase oversampling.

Table A14.1.5 Primary Clinical Imaging Parameters for 2-D Sagittal T_1-Weighted Spin Echo (Sequence 4)

Patient position	Supine
Scan type	Spin echo
Imaging plane (orientation)	Sagittal
Central slice or volume center	Symptomatic brachial plexus
Echo time (T_E)	14 msec
Repeat time (T_R)	600 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	200 mm, 200 mm
Resolution (Δx, Δy)	0.78 mm, 1.04 mm
Number of data points collected (N_x, N_y)	256, 192[a]
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	5 mm
Number of slices	20
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Swap read and phase encoding	No
Saturation pulses	Inferior over the heart
Scan time	4 min, 39 sec

[a]20% phase oversampling.

Table A14.1.6 Primary Clinical Imaging Parameters for 2-D Sagittal T_2-Weighted Turbo Spin Echo with Fat Suppression (Sequence 5)

Patient position	Supine
Scan type	Fast spin echo
Imaging plane (orientation)	Sagittal
Central slice or volume center	Symptomatic brachial plexus
Echo time (T_E)	99 msec
Echo train length (ETL)	11
Repeat time (T_R)	3980 msec
Flip angle (FA)	160°[a]
Fields of view (FOV_x, FOV_y)	200 mm, 200 mm
Resolution (Δx, Δy)	0.78 mm, 1.04 mm
Number of data points collected (N_x, N_y)	256, 192[b]
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	5 mm
Number of slices	20
Slice gap	1 mm
Number of acquisitions (N_{acq})	3
Swap read and phase encoding	No
Saturation pulses	Fat suppression
Scan time	4 min, 16 sec

[a]The system displays the flip angle of the refocusing pulse. The flip angle of the first pulse of this sequence is 90°.
[b]20% phase oversampling.

Table A14.1.7 Primary Clinical Imaging Parameters for 2-D Sagittal Inversion Recovery Turbo Spin Echo (Sequence 6)

Patient position	Supine
Scan type	Inversion recovery turbo spin echo
Imaging plane (orientation)	Sagittal
Central slice or volume center	Symptomatic brachial plexus
Echo time (T_E)	30 msec
Echo train length (ETL)	7
Repeat time (T_R)	5400 msec
Inversion time (T_I)	155 msec
Flip angle (FA)	160°
Fields of view (FOV_x, FOV_y)	200 mm, 200 mm
Resolution (Δx, Δy)	0.78 mm, 1.04 mm
Number of data points collected (N_x, N_y)	256, 192[a]
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	5 mm
Number of slices	20
Slice gap	1 mm
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
Saturation pulses	Inferior over the heart
Scan time	2 min, 59 sec

[a]20% phase oversampling.

Table A14.1.8 Primary Clinical Imaging Parameters for 2-D Sagittal Flow Sensitive Gradient Echo (Sequence 7)

Patient position	Supine
Scan type	2-D gradient echo
Imaging plane (orientation)	Sagittal
Central slice or volume center	Symptomatic brachial plexus
Echo time (T_E)	9 msec
Repeat time (T_R)	30 msec
Flip angle (FA)	30°
Fields of view (FOV_x, FOV_y)	200 mm, 200 mm
Resolution (Δx, Δy)	0.78 mm, 1.04 mm
Number of data points collected (N_x, N_y)	256, 192[a]
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	5 mm
Number of slices	20
Slice gap	1 mm
Number of excitations (NEX)	20[b]
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
Flow compensation	Yes
Saturation pulses	No
Scan time	2 min, 20 sec

[a]20% phase oversampling.

[b]The number of concatenation is set to be 20. This means that only one slice will be excited during a given repeat time.

Sequence 5: 2-D Sagittal T_2-weighted turbo spin echo sequence with fat suppression of symptomatic brachial plexus

17. Positioning is the same as sequence 4. Run sequence 5 according to Table A14.1.6.

The T_2-weighted sequence is useful in characterizing the lesions in the brachial plexus.

Sequence 6: 2-D Sagittal inversion recovery turbo spin echo sequence of symptomatic brachial plexus (optional)

If the fat suppression is not adequately obtained with sequence 5, inversion recovery turbo spin echo sequence is an alternative sequence.

18. Positioning is same as sequence 4. Run sequence 6 according to Table A14.1.7.

Sequence 7: 2-D Sagittal flow sensitive gradient echo sequence of symptomatic brachial plexus (optional)

This sequence is an optional sequence, and can be performed to help differentiate vascular structures from lesions.

19. Positioning is the same as sequence 4. Run sequence 7 according to Table A14.1.8.

IMAGING OF BRACHIAL PLEXUS FOR AVULSION INJURY

ALTERNATE PROTOCOL 1

For patients with suspected avulsion injury of the nerve root, the Basic Protocol should be modified and a coronal T_2-weighted sequence of bilateral brachial plexus as well as a transverse T_2-weighted sequence of the symptomatic side are added. The sagittal T_2-weighted turbo spin-echo sequences in the Basic Protocol can be omitted.

Set up patient and equipment

1. Use the same equipment and the same patient setup as for the previous method (see Basic Protocol, steps 1 to 9).
2. Run the same sequences 1 to 4 in Basic Protocol (see Basic Protocol, steps 10 to 16).

Table A14.1.9 Primary Clinical Imaging Parameters for 2-D Coronal T_2-Weighted Turbo Spin Echo (Sequence 8)

Patient position	Supine
Scan type	Fast spin echo
Imaging plane (orientation)	Coronal
Central slice or volume center	Midline
Echo time (T_E)	99 msec
Echo train length (ETL)	13
Repeat time (T_R)	4200 msec
Flip angle (FA)	160°[a]
Fields of view (FOV_x, FOV_y)	375 mm, 375 mm
Resolution (Δx, Δy)	0.73 mm, 1.39 mm
Number of data points collected (N_x, N_y)	512, 270[b]
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	5 mm
Number of slices	15
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Swap read and phase encoding	No
Saturation pulses	Inferior and superior
Scan time	3 min, 59 sec

[a]The system displays the flip angle of the refocusing pulse. The flip angle of the first pulse of this sequence is 90°.
[b]30% phase oversampling.

Table A14.1.10 Primary Clinical Imaging Parameters for 2-D Transverse T_2-Weighted Turbo Spin Echo with Fat Suppression (Sequence 9)

Patient position	Supine
Scan type	Turbo spin echo
Imaging plane (orientation)	Transverse
Central slice or volume center	Symptomatic brachial plexus
Echo time (T_E)	99 msec
Echo train length (ETL)	11
Repeat time (T_R)	4200 msec
Flip angle (FA)	160°
Fields of view (FOV_x, FOV_y)	200 mm, 200 mm
Resolution (Δx, Δy)	0.78 mm, 1.04 mm
Number of data points collected (N_x, N_y)	256, 192[a]
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	5 mm
Number of slices	20
Slice gap	1 mm
Number of acquisitions (N_{acq})	3
Swap read and phase encoding	No
Saturation pulses	Fat suppression
Scan time	4 min, 41 sec

[a]20% phase oversampling.

Sequence 8: 2-D Coronal T_2-weighted turbo spin echo sequence of bilateral brachial plexus

3. Position a series of coronal slices off the scout images to ensure coverage of the bilateral brachial plexus by including both acromioclavicular joints from side to side, and mid C4 to below axilla from top to bottom. From anterior to posterior, start from slightly anterior to the subclavian and axillary artery to slightly posterior to the neural foramina of C4 to T1.

   This is a high-resolution sequence and fat suppression is not used.

4. Run sequence 8 according to Table A14.1.9.

Sequence 9: 2-D Transverse T_2-weighted turbo spin echo sequence of symptomatic brachial plexus (with fat suppression)

5. Position a series of transverse slices off the coronal images to ensure coverage of the symptomatic brachial plexus by including mid vertebral body to the acromioclavicular joint from side to side, and mid C4 to axilla from top to bottom.

6. Run sequence 9 according to Table A14.1.10.

ALTERNATE PROTOCOL 2

IMAGING OF BRACHIAL PLEXUS FOR NEOPLASTIC INVOLVEMENT

If neoplastic involvement of the brachial plexus is suspected, the Basic Protocol should be modified. Pre- and post-contrast T_1-weighted spin-echo with fat suppression should be performed. The post-contrast sequence increases the sensitivity to detect abnormalities and help characterize the lesions. The image plane should be chosen which best depicts the abnormality.

Materials

Normal saline (0.9% NaCl), sterile
Gadolinium-based MR contrast agent (e.g., Magnevist, Omniscan, or Prohance)
22-G intravenous catheter
Power injector (optional)

Set up patient and equipment

1. Use the same equipment and the same patient setup as for the previous method (see Basic Protocol, steps 1 to 8).
2. Place a 22-G intravenous catheter in the antecubital fossa. Establish an intravenous line from which the contrast agent can be injected, and attach this line securely to the patient so that movement into or out of the magnet will not pull at the patient's arm.

   It is preferable to insert the line prior to imaging and to leave the patient in the magnet, with no intervening motion between the scans run before contrast agent injection and those run after injection.

3. Use the centering light to position the patient with the center at the patient's sternum and put him or her into the center of the magnet.
4. Run the same sequences 1 to 7 in Basic Protocol (see Basic Protocol, steps 10 to 19).

Sequence 10: 2-D T_1-weighted spin echo sequence with fat suppression of symptomatic brachial plexus before contrast agent injection

5. Choose the image plane which best depicts the lesion and run sequence 10 according to Table A14.1.11. If no lesions are seen, choose transverse plane.

Table A14.1.11 Primary Clinical Imaging Parameters for 2-D T_1-Weighted Spin Echo with Fat Suppression (Sequences 10 and 11)

Patient position	Supine
Scan type	Spin echo
Imaging plane (orientation)	The one that can best depict the lesion
Central slice or volume center	Symptomatic brachial plexus
Echo time (T_E)	12 msec
Repeat time (T_R)	410 msec[a]
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	200 mm, 200 mm
Resolution (Δx, Δy)	0.78 mm, 1.04 mm
Number of data points collected (N_x, N_y)	256, 192[b]
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	5 mm
Number of slices	20
Slice gap	2 mm
Number of acquisitions (N_{acq})	3
Swap read and phase encoding	No
Saturation pulses	Fat suppression
Scan time	6 min, 35 sec

[a] T_R of 600 msec or less is preferred, if possible. This can be achieved in systems which can concatenate the acquisition. If the system does not allow concatenation of the sequence, two sets of 10 slices can be obtained separately.
[b] 20% phase oversampling and a phase partial Fourier factor of 11/16.

Sequence 11: 2-D T_1-weighted spin echo sequence with fat suppression of symptomatic brachial plexus after contrast agent injection

6. Leaving the patient in the magnet, administer 0.1 mmol/kg gadolinium contrast intravenously. Flush the catheter with 5 ml normal saline. Run sequence 11 according to Table A14.1.11.

   The image plane and position should be same as sequence 10.

ALTERNATE PROTOCOL 3

CONTRAST-ENHANCED MRA FOR THORACIC OUTLET SYNDROME

When thoracic outlet syndrome with vascular compromise is suspected, contrast-enhanced MRA can be added to the Basic Protocol. Two series of MRA images are obtained with the patient's arm in neutral position and above the shoulder. Double-dose gadolinium contrast (e.g., 40 ml) is divided into half for each series. After the test bolus, one measure for a pre-contrast mask and two measures for post-contrast MRA are obtained for each series.

Materials

Normal saline (0.9% NaCl), sterile
Gadolinium-based MR contrast agent (e.g., Magnevist, Omniscan, or Prohance)
Power injector (for the MRA technique)

Set up patient and equipment

1. Use the same equipment and the same patient setup as for the previous method (see Basic Protocol, steps 1 to 8).
2. Place a 22-G intravenous catheter in the antecubital fossa of the asymptomatic arm. Establish an intravenous line from which the contrast agent can be injected, and attach this line securely to the patient so that movement into or out of the magnet will not pull at the patient's arm.

   Load the injection with a double dose (0.2 mmol/kg) of gadolinium contrast agent (this is usually 40 ml or less).

   It is preferable to insert the line prior to imaging and to leave the patient in the magnet, with no intervening motion between the scans run before contrast agent injection and those run after injection.

   When the contrast material is injected from the symptomatic side, the vessels may appear artificially narrowed and simulate disease on the MRA sequence because of the high-concentration of contrast material and the accompanying T_2 shortening effect. To avoid this artifact, the catheter should be placed in the asymptomatic arm.

3. Use the centering light to position the patient with the center at the patient's sternum and put him or her into the center of the magnet.
4. Use the same sequences 1 to 7 as in the Basic Protocol (see Basic Protocol, steps 10 to 19).

Sequence 12: Test bolus

5. Position a single transverse slice at the level of the aortic arch on screen.
6. Set up the injector for injection of 2 ml of gadolinium followed by 15 ml normal saline at the rate of 2 ml/sec.
7. As you start the injector, start sequence 12 according to Table A14.1.12.

   The sequence will acquire a single slice every second for 50 sec at the same location.

8. By scrolling the images, determine the time to the peak of contrast bolus arrival from the start of contrast agent injection.

Sequence 13: 3-D Pre-contrast MRA with the arm in neutral position (mask)

The pre-contrast sequence is obtained as a mask for subtraction and to ensure the coverage and image quality.

9. Position the slab in coronal plane to cover the aortic arch and bilateral subclavian arteries. Run sequence 13 according to Table A14.1.13 under breath-hold in inspiration.

Table A14.1.12 Primary Clinical Imaging Parameters for Test Bolus (Sequence 12)

Patient position	Supine
Scan type	Gradient echo
Imaging plane (orientation)	Transverse
Central slice or volume center	Aortic arch
Echo time (T_E)	2.4 msec
Repeat time (T_R)	5.8 msec
Inversion time (T_I)	300 msec
Flip angle (FA)	15°
Fields of view (FOV_x, FOV_y)	400 mm, 300 mm
Resolution (Δx, Δy)	1.56 mm, 2.34 mm
Number of data points collected (N_x, N_y)	256, 128
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	10 mm
Number of slices	1
Slice gap	Not applicable
Number of acquisitions (N_{acq})	50
Swap read and phase encoding	No
Saturation pulses	No
Scan time	50 sec

Table A14.1.13 Primary Clinical Imaging Parameters for 3-D MRA, Mask (Sequence 13)

Patient position	Supine
Scan type	3-D gradient echo
Imaging plane (orientation)	Coronal
Central slice or volume center	Midline
Echo time (T_E)	1.8 msec
Repeat time (T_R)	4.6 msec
Flip angle (FA)	25°
Fields of view (FOV_x, FOV_y)	375 mm, 375 mm
Resolution (Δx, Δy)	1.46 mm, 2.21 mm
Number of data points collected (N_x, N_y)	256, 170
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	3 mm (1.5 mm after interpolation)
Number of slices	34 (68 after interpolation)
Slice gap	0 mm
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
ZIP 2	Yes
Saturation pulses	No
Scan time	21 sec

10. Check the images to ensure the coverage of the bilateral subclavian arteries and aortic arch.

    Minimal wrapping artifact does not interfere with the diagnostic ability of the study. The degree of respiration artifact should be checked. If the patient cannot hold their breath long enough, consideration should be given to shorten the scan time at the cost of spatial resolution.

Sequence 14: 3-D Contrast-enhanced MRA with the arm in neutral position

11. Set up the injector for injection of half of the gadolinium (~19 ml) followed by 15 ml normal saline at the rate of 2 ml/sec.

    At this point, 21 ml of gadolinium is used (2 ml of gadolinium was used in the test bolus, sequence 12). The other half of the gadolinium will be used in sequence 16, step 17.

12. Scan delay from the start of injection can be calculated based on time to peak of contrast agent arrival determined by test bolus injection, injection duration, and scan duration using following formula:

    scan delay = time to peak + (injection duration)/2 − (scan duration)/2.

    The scan time is typically 25 sec and injection duration is 9.5 sec (19 ml at 2 ml/sec). If the time to peak at test injection is 15 sec, the scan delay would be 7 sec (= 15 + 9.5/2 − 25/2).

13. Position the slab exactly the same as in sequence 13.

    The position should be copied from "history" so that subtraction can be performed later. Two measures are performed in this sequence, and ~8-sec interval should be allowed for the patient to breathe between the first and second measures.

14. Start the injector, and after the scan delay as calculated in step 12, run sequence 14 according to Table A14.1.14 using a breath-hold in inspiration.

Sequence 15: 3-D Pre-contrast MRA with the arm above the shoulder (mask)

Even though the contrast agent has been injected during the previous scan, the word "pre-contrast" is still used here to distinguish this sequence from sequence 16.

15. Change the patient's arm position to above the shoulder.

16. Repeat steps 9 and 10 in this alternate protocol.

Sequence 16: 3-D Contrast-enhanced MRA with the arm above the shoulder

17. Set up the injector for the injection of the remaining gadolinium (~19 ml), followed by 15 ml normal saline at the rate of 2 ml/sec.

18. Repeat steps 11 to 14 in this alternate protocol.

    Sequences 15 and 16 are exactly the same as sequences 13 and 14 except for the arm position.

Data processing and viewing for sequences 13 to 16

19. Create subtraction data set from the pre- and post-contrast MRA sequences for each arm position. Subtraction is essential for the second run (sequences 14 and 16) to eliminate venous contamination from the first run. Display these data sets in maximal intensity projection (MIP) and multi-planar reconstruction (MPR).

Table A14.1.14 Primary Clinical Imaging Parameters for 3-D Contrast Enhanced MRA (Sequence 14)

Patient position	Supine
Scan type	3-D gradient echo
Imaging plane (orientation)	Coronal
Central slice or volume center	Midline
Echo time (T_E)	1.8 msec
Repeat time (T_R)	4.6 msec
Flip angle (FA)	25°
Fields of view (FOV_x, FOV_y)	375 mm, 375 mm
Resolution (Δx, Δy)	1.46 mm, 2.21 mm
Number of data points collected (N_x, N_y)	256, 170
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	3 mm (1.5 mm after interpolation)
Number of slices	34 (68 after interpolation)
Slice gap	0 mm
Number of acquisitions (N_{acq})	1
Number of repetitions	2 (with 8-sec time interval in between)
Swap read and phase encoding	No
ZIP 2	Yes
Saturation pulses	No
Scan time	21 sec (50 sec with two repetitions)

COMMENTARY

Background Information

The brachial plexus provides motor and sensory innervation to the upper extremity. A variety of imaging techniques including computed tomography (CT) and myelography have been used in the past for assessment of the brachial plexus. Currently, MR is considered the modality of choice because of its multi-planar capability and good soft tissue contrast (Posniak et al., 1993).

The brachial plexus is formed by the C5 to T1 nerve roots, with inconstant contributions from C4 and T2 nerve roots. The brachial plexus courses anterolaterally to pass between the anterior and middle scalene muscles, where the three trunks are formed. Each trunk is divided into two to four divisions, which run along the superior aspect of the subclavian artery in the supraclavicular fossa. Three cords are formed from divisions, which run around the axillary artery in the axilla.

Symptoms of brachial plexopathy include numbness, pain or weakness involving multiple root levels and multiple peripheral nerves. Brachial plexopathy may be caused by various pathologic entities including trauma, primary neurogenic tumors or secondary neoplasms, radiation injury, and neuritis.

Critical Parameters and Troubleshooting

Fat suppression is used with the T_2-weighted turbo spin echo sequence. Fat suppression may not be effective in some patients partly due to field inhomogeneity near the surface of the body. In those instances, use an inversion recovery sequence (sequence 6) to achieve fat suppression.

Some authors advocate the use of ECG gating or respiratory compensation to eliminate cardiac pulsatility or respiratory motion artifact. The protocols described herein do not call for the use of these techniques. If necessary, ECG gating or respiratory compensation can be used.

The only breath-hold sequence is the contrast-enhanced MRA sequence for suspected thoracic outlet syndrome with vascular compression. If the patient cannot hold his or her breath for the period of the sequence (typically 22 to 25 sec), decrease the number of phase encoding steps (N_y, or number of acquisitions) to reduce the scan time.

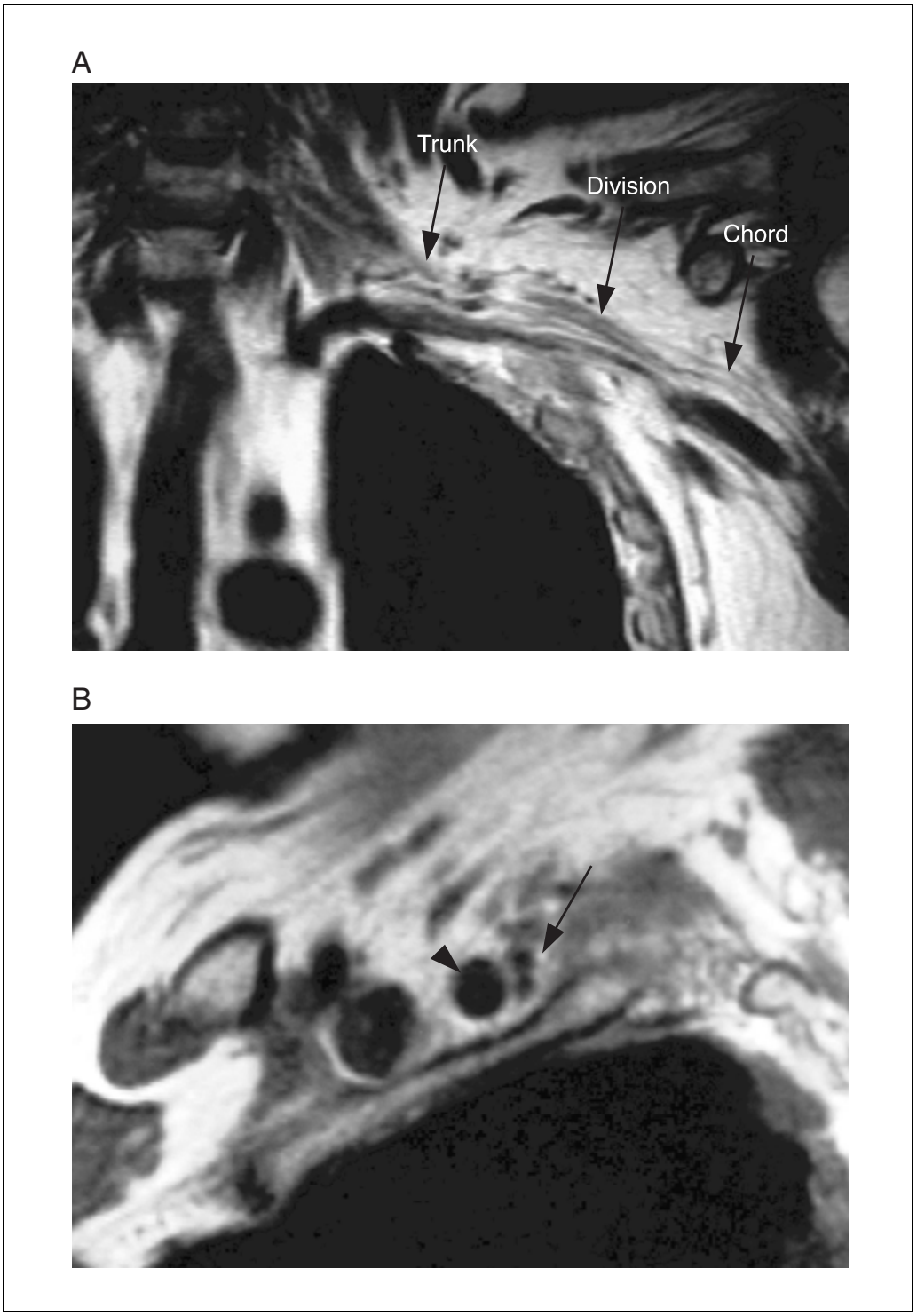

Figure A14.1.1 Normal brachial plexus. (**A**) Coronal and (**B**) sagittal T_1-weighted images demonstrate normal brachial plexus (arrows), which is a thin linear structure surrounded by fat and running along the subclavian artery (arrow heads).

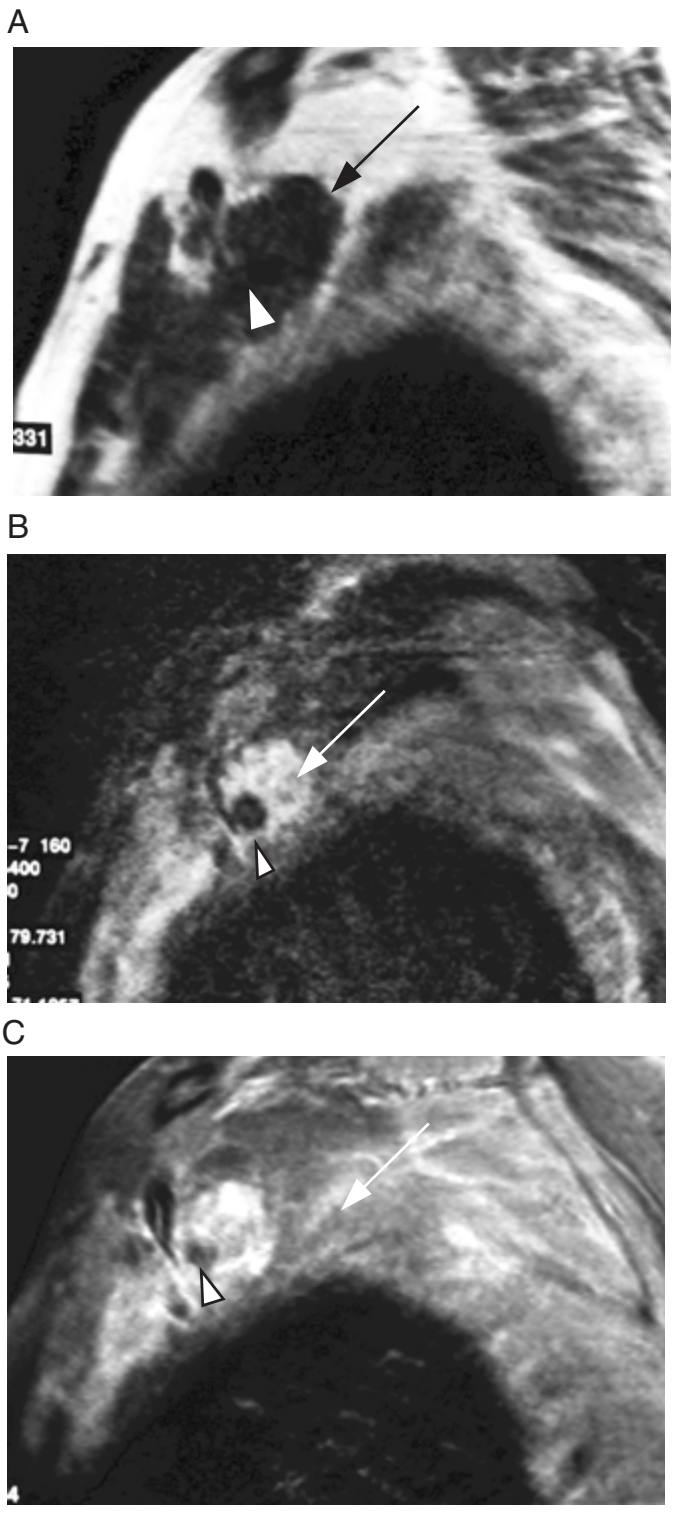

Figure A14.1.2 Brachial plexus involved by metastatic breast carcinoma. (**A**) Sagittal T_1-weighted image shows an isointense soft tissue mass (arrow) encasing the brachial plexus and subclavian artery (arrow head). (**B**) On inversion recovery image, the mass is hyper-intense (arrow). The subclavian artery (arrow head) is encased by the mass. (**C**) After administration of gadolinium contrast, the mass shows enhancement (T_1-weighted image with fat saturation) (arrow). Note the encasement of the subclavian artery (arrow head) by the mass.

Anticipated Results

On T_1-weighted images, the normal brachial plexus appears as low signal fine linear structure that runs along the subclavian and axillary artery (Fig. A14.1.1A, A14.1.1B). T_1-weighted images are best for delineation of anatomy because of good soft tissue contrast between fat and brachial plexus. T_2-weighted images and post-contrast T_1-weighted images are good at characterizing lesions.

Brachial plexopathy may result from penetrating or nonpenetrating trauma. Nonpenetrating injuries include avulsion injury, compression by adjacent fractures, or hematomas. On MR, avulsion injury is recognized by a thickened, folded appearance of the brachial plexus and pseudomeningocele formation.

Primary neurogenic neoplasms are usually intermediate in signal intensity on the T_1-weighted image and bright in signal intensity

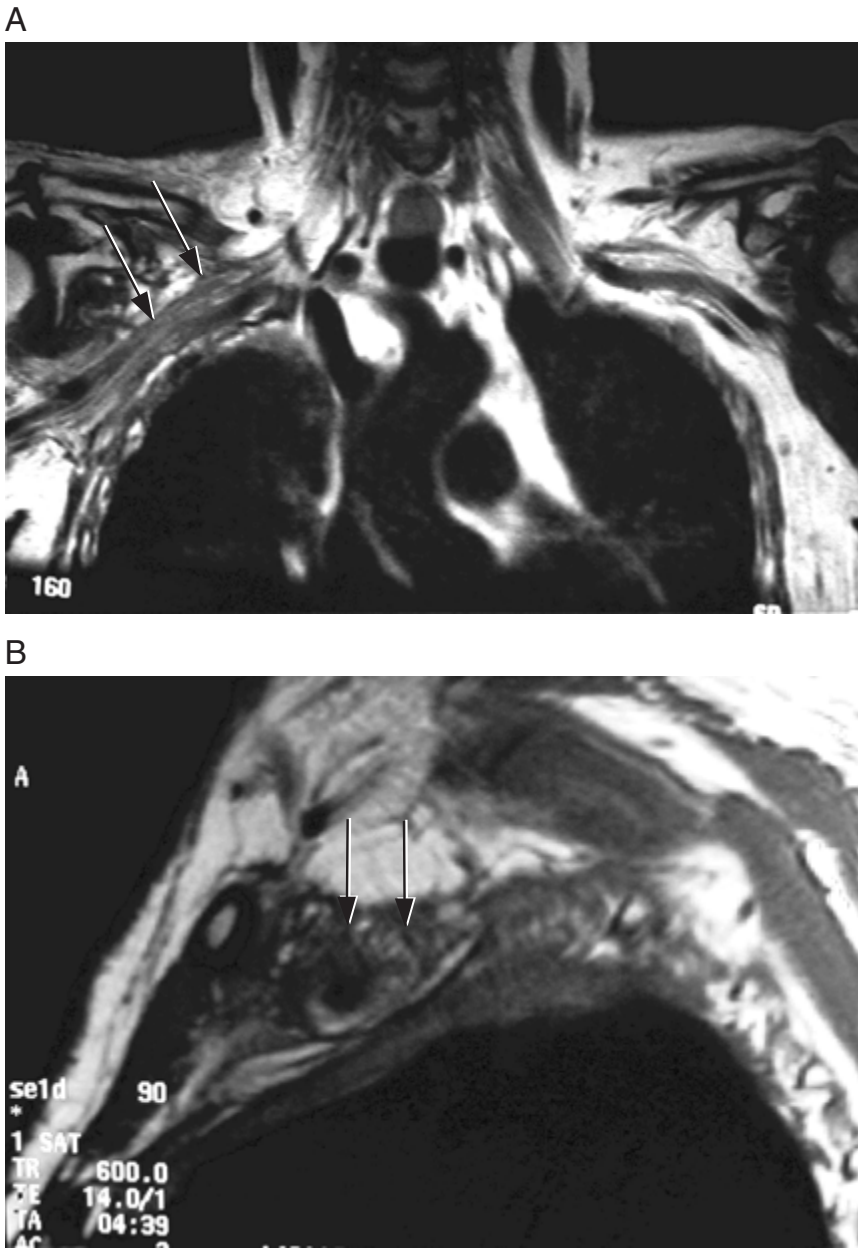

Figure A14.1.3 Radiation fibrosis involving brachial plexus. (**A**) Coronal and (**B**) sagittal T_1-weighted images demonstrate soft tissue strands and loss of fat plane surrounding the right brachial plexus (arrows). Compare with the normal brachial plexus on the left in the coronal image.

on the T_2-weighted image, and fusiform to round in shape. After gadolinium administration, such neoplasms are typically enhanced.

Involvement of the brachial plexus by secondary tumor is much more common than primary neurogenic tumors. The most common secondary tumors to involve brachial plexus are lung and breast carcinomas (Wittenberg and Adkins, 2000). The brachial plexus may be involved by tumors by direct extension as in Pancoast tumor (lung carcinoma) or indirectly from lymph node metastasis (Fig. A14.1.2).

Radiation brachial plexopathy can occur 18 months to 10 years after the radiation therapy. It should be differentiated from recurrence of the tumor. Evidence of edema (high signal on the T_2-weighted image) or fibrosis (low signal on the T_2-weighted image) depending on the phase of radiation injury and lack of mass lesion are the hallmark of MR findings (Fig. A14.1.3) (Glazer et al., 1985; Bowen et al., 1996; Thyagarajan et al., 1995).

Brachial plexus neuritis can be caused by various different etiologies or can be idiopathic. On MR, the brachial plexus is thickened and high in signal intensity on T_2-weighted images.

Thoracic outlet syndrome occurs because of compression of brachial plexus or subclavian artery in the scalene triangle or costoclavicular space. Underlying skeletal abnormalities such as a cervical rib or a fracture deformity of clavicle or first rib can be responsible for the compression. Other causes include fibromuscular band or spasm of scalene muscle. The compression is often positional and subtle, these abnormalities may be difficult to identify. When vascular compression is present, a contrast enhanced MRA sequence may show change in the caliber of the subclavian artery in the position that produces the symptom.

Literature Cited

Bowen, B.C., Verma, A., Brandon, A.H., and Fiedler, J.A. 1996. Radiation induced brachial plexopathy: MR imaging with clinical correlation. *Am. J. Neuroradiol.* 17:1932-1936.

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Thyagarajan, D. Cascino, T., and Harms, G. 1995. Magnetic resonance imaging in brachial plexopathy of cancer. *Neurology* 45:421-427.

Wittenberg, K.H. and Adkins, M.C. 2000. MR imaging of nontraumatic brachial plexopathies: frequency and spectrum of findings. *Radiographics* 20:1023-1032.

Key References

Posniak et al., 1993. See above.

Covers overview of MR appearances of various diseases involving brachial plexus.

Shellock, 1996. See above.

Covers a number of important patient management issues related to MR imaging, including recommended safety procedures, a list of metallic implants that have been tested for MR compatibility, and a list of other sources on MR safety.

Wittenberg and Adkins, 2000. See above.

Covers overview of MR appearances of various diseases involving brachial plexus.

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